Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

DTIC ELECTE AUG 15 1988 H

DTIC FILE COPY

AD-A198 792

1b. RESTRICTIVE MARKINGS
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3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release
distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
Dept. Anatomy and Neurobiology
University of Tennessee, Memphis

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 88-0691

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
		AFOSR-NL

6c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
University of Tennessee, Memphis 875 Monroe Avenue, Memphis, TN 38163	Building 410 Boliing AFB, D.C. 20332-6448

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR	NL	AFOSR 85-0217

8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
Buliding 410 Bolling AFB, D.C. 20332-6448	61102F	2312	A2	

11. TITLE (Include Security Classification)
Changes in Somatosensory Responsiveness in Behaving Primates - Unclassified

12. PERSONAL AUTHOR(S)
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13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final Technical	FROM 7/1/85 TO 6/30/88	01-AUG-88	29

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Changes in sensory responsiveness; response gating; human and primate reaction times; visual and vibratory cues

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The four specific goals of the research conducted were: 1) to train monkeys to perform sensory-triggered wrist movement tasks in preparation for electrophysiological recording and to study their reaction times for visually vs. vibratory-triggered movements; 2) to record from the cerebral cortex of awake, behaving monkeys during the performance of these sensory-triggered wrist movement tasks; 3) to analyze data obtained from electrophysiological and behavioral recording to better understand the occurrence of sensory gating during the execution of stereotyped behaviors; 4) to train human subjects to perform the same tasks as those require of the monkeys to determine the differences in human reaction times for hand movements made in response to visual and vibratory cues so that the human results could be compared with the monkey data.

We have determined that: 1) The premovement activity that occurs in primary somatosensory cortical neurons differs in timing and magnitude, depending upon the type of sensory cue used to trigger hand movements. 2) The magnitude of the premovement activity during vibratory-cued trials is related to how responsive a given neuron is to vibratory stimuli. 3) Humans and monkeys make hand movements more quickly in response to vibratory as compared with visual go cues.

Our main goal was to better understand the performance limitations imposed by the nervous system on subjects that are required to control devices by responding to sensory cues with appropriate corrective and/or controlled hand movements.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
William O. Berry, Ph.D.	202-767-5021	NL

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

9 AUG 1988

Research Objectives:

The four specific goals of the research conducted during the three years of this grant were: 1) to train monkeys to perform sensory-triggered wrist movement tasks in preparation for electrophysiological recording and to study their reaction times for visually vs. vibratory-triggered movements; 2) to record from the cerebral cortex of awake, behaving monkeys during the performance of these sensory-triggered wrist movement tasks; 3) to analyze data obtained from electrophysiological and behavioral recording to better understand the occurrence of sensory gating during the execution of stereotyped behaviors; 4) to train human subjects to perform the same tasks as those require of the monkeys to determine the differences in human reaction times for hand movements made in response to visual and vibratory cues so that the human results could be compared with the monkey data. Our main goal continues to be to better understand the performance limitations imposed by the nervous system on subjects that are required to control devices by responding to sensory cues with appropriate corrective and/or controlled hand movements.

Status of Current Research - Statement of Work:

To date the activity of 399 neurons have been recorded from two monkeys trained to perform the tasks described below. Two additional monkeys have been trained to perform these tasks and another two monkeys await the start of training. Of these 399 neurons, 176 have been defined as being located in the cortical regions comprising primary somatosensory cortex (SI). Another 173 are presumed to be within SI, but since the animal from which these recordings were made is still yielding excellent data, we have not sacrificed him to do the histology necessary to confirm the location of the recording sites.

In the descriptions of work contained below, all analyses described were done on sub-populations of neurons that have been histologically confirmed as located in SI. It should be noted that, for each of the electrophysiological studies, analyses described have been performed on each neuron whose location has yet to be confirmed. Once this monkey is sacrificed, the populations neurons involved in each analysis will approximately double to triple. We thought it only prudent to include the results from only those neurons with confirmed SI locations in this report.

The work describe consists of three separate studies. The first compares the activity of SI neurons that occurs before active movement of the hand in response to vibratory or visual go signals. The object of this study was to determine if the premovement activity under these two conditions occurred at the same time before movement onset and if it was of the same magnitude under the two stimulus-response conditions. Based on the results of this first study, the study whose description follows was undertaken to determine the nature of the relationship between a neuron's responsiveness to vibratory stimuli and the magnitude of the premovement activity that follows the stimulus response, yet precedes movement onset. The third study describes our pilot experiments in which we sought to determine if movements made in response to vibratory cues begin more quickly than those made in response to visual cues. In these ongoing investigations, we seek to determine the capacities of the human nervous system for quickly processing externally generated sensory signals in order to suggest new ways in which sensory information can be presented and used to control complex devices through accurate and timely execution of hand movements.

Methods - Primate Neurophysiological Studies

Behavioral paradigm

Adult male rhesus monkeys (*Macaca mulatta*) were used in the present experiments. They were cared for in accordance with the *NIH Guide for Care and Use of Laboratory Animals, revised 1985*. Each monkey was seated in a plexiglas primate chair and trained to make wrist flexion or extension movements, against or with a 0.07 Nm load assisting extension while they viewed a visual display placed 35cm in front of them. This display consisted of a central, larger, red light-emitting diode (LED) and vertical rows of smaller, yellow LEDs and was coupled to the output of the wrist position transducer so that each successively illuminated LED from the central lamp corresponded to an angular deflection of 1° from the central position. The animal's hand rested on an aluminum handle which the animal moved to receive a fruit juice reward if a movement of at least 5° was made in the appropriate direction. The behavioral tasks consisted of two trigger stimulus conditions in which movements were triggered by either a visual or one of three vibratory cues after the animal had maintained a centered wrist position for a period of time chosen randomly, but ranging between 0.5 and 2.0 sec. Vibratory cues consisted of vibrating the handle with a low-amplitude sine wave at either 27, 57 or 127 Hz. Visual cues consisted of adding or subtracting a DC voltage from the coupled wrist position signal, resulting in a shift in the illuminated lamp in the opposite direction from the requested movement by an amount equal to that required to re-center the display . Flexion and extension movements were requested in alternating blocks of ten trials each. Vibratory and visual cues were presented in blocks of eighty trials each. At the start of each trial, visual indicators consisting of two additional LEDs placed in the upper left corner of the visual display were presented which instructed each animal as to the direction of the required movement and the type of trigger stimuli that would be presented. Once the animals learned to perform the tasks reliably, usually from 8-12 weeks, they were prepared for chronic cortical single-unit recording.

Surgical procedures and daily preparations

Each monkey was anesthetized with pentobarbital (33.3 mg/kg) or Halothane followed by pentobarbital after induction with ketamine hydrochloride (10 mg/kg) and placed in a stereotaxic device. Stainless steel bolts were implanted for head immobilization and secured with methyl methacrylate (Howmedica Surgical Simplex P). A stainless steel recording chamber was implanted over the forelimb region of the left sensorimotor cortices following a craniotomy and secured with smaller bolts and the surgical cement. The incision was closed in layers and local antibiotics (Furazone and bacitracin-neomycin-polymyxin ointment) were applied to the wound. The chamber was filled with sterile saline and 1cc of Chloramphenicol (4mg/cc) and sealed with a translucent acrylic plate.

During the first post-operative week, each monkey was acclimated to behaving with his head restrained. Thereafter daily recording sessions were conducted. Each day, the chamber was flushed with normal saline and refilled. A microdrive with adapter (Narishige MO-95B) was attached to the acrylic plate. While the monkeys performed the task, transdural electrode penetrations were made using glass-coated, platinum-iridium microelectrodes (0.7-1.5 M Ohms, 1Khz) to record the neuronal activity of single neurons in the sensorimotor cortices. Upon completion of each daily session, the chamber was flushed with sterile saline and 1.0cc of Chloramphenicol was added to the chamber solution to retard infection.

Recording and data analysis

The activity of single cortical neurons was recorded by conventional means. The output of the head-stage preamplifier was amplified and bandpass filtered at 500 Hz and 10 KHz. Single-unit discharges were discriminated using a window discriminator. Neuronal activity, wrist position and the onset of trigger stimuli, as well as other significant behavioral events, were digitized by a PDP-11/23 microcomputer using an on-line data collection routine with a temporal resolution of 100 μs. Recordings were stored for later off-line data analysis. The on-line program also ran the behavioral task and handled the alternation of trigger stimulus type and requested movement direction as well as the randomization of the hold period necessary prior to the delivery of the vibratory or visual go-cues. The position of the handle which indicated the animal's wrist position was sampled at 10 ms intervals.

A second, off-line data analysis computer program was used to generate displays of the neuronal activity in the form of rasters, peri-event time histograms, and analog displays of the wrist position aligned with the neuronal records. Measurements of the mean background activity of each neuron during the hold period (when the animal maintained a constant position) were made. Significant non-stimulus related premovement activity was operationally defined as any change in the mean firing rate that was not associated with stimulus onset and that was either greater than or less than the mean background activity by 50% for 30 consecutive msec. This was accomplished using a moving average algorithm that scanned the peri-event time histograms and compared the discharge in each 30 msec period to the calculated background mean discharge rate. The onset of each premovement change was defined as starting at the beginning of the first 30 msec period time before movement onset during which a significant change occurred. The magnitude of each change was calculated as the mean firing rate during this premovement interval minus the mean background activity. If more than one vibratory frequency was tested, the values from the block of trials at a given frequency that exhibited the most robust change in activity were used, assuming that those trials indicated the neuron's optimal capacity for premovement activity.

Premovement activity changes for selected blocks of trials triggered by visual and vibratory stimuli were then compared. In this comparison, the onset of the premovement activity during the visually cued trials was subtracted from the onset calculated during the trials cued by the vibratory stimulus. In a similar manner, the magnitude of the premovement activity change preceding movements made in response to the vibratory go-cue was subtracted from the magnitude of the activity change exhibited during visually cued trials. The resulting differences calculated for those neurons recorded in cortical areas comprising SI were plotted on histograms (figure 3). A paired t-test was done for the onset differences and the magnitude differences for each direction of requested movement. These differences were considered significant if their probability values resulting from the t-test were less than or equal to 0.01.

Whenever possible, the peripheral receptive field (RF) of each cortical neuron was explored. Tactile stimuli presented outside the task consisted of light stimulation with hand-held probes or an anesthesiometer (Rowan). Cells were classified as responding to deep stimulation if: 1) they did not respond faithfully to light tactile stimuli and 2) they responded to bending of joints or palpation of muscle bellies. To insure that stimulation of overlying skin was not mistaken as a response from a muscle, the skin was displaced laterally and the muscle again palpated. No neurons having complex RFs or mixed cutaneous and deep RFs are presented in this study.

Histological procedures

In the final session for each monkey, electrolytic lesions were made at points of interest by passing direct current (10 μA for 20 sec) through a recording electrode. Animals were deeply anesthetized with pentobarbital and perfused intracardially with 10% buffered Formol-saline. During the perfusion, stainless steel marking pins were inserted into the hemispheres through guide-tubes placed in a specially constructed chamber cap so that they would be in the plane of the electrode penetrations and at the boundaries of the recording area. The sensorimotor cortex was removed from the rest of the brain and cut in 50μ sections on a freezing microtome in a parasagittal plane that was orthogonal to the plane of the electrode penetrations.

Electrode penetrations were reconstructed based on previously determined criteria: 1) the point of entry of the electrode at the cortical surface, 2) the depth of each recording site, 3) the surface morphology [30] and 4) the position of marking lesions and guide pin placements. Recording sites were assigned to cortical areas based on previously descriptions of the cytoarchitectonic characteristics of areas 4, 3a, 3b, 1, and 2.

Methods - Psychophysical Studies of Human and Primate Reaction Times

Human Subjects

Eight young adult volunteers were asked to perform the paradigm described below. Each was asked to perform the task with their perferred hand. All had normal or corrected-to-normal vision and had normal hearing. The subjects received no compensation for their efforts, yet remained enthusiastically devoted to the task throughout the duration of testing.

Procedure

Each subject was seated in a comfortable chair in a quiet, moderately lit room and was instructed to make wrist flexion or extension movements as quickly as possible, against or with a 0.12 Nm load assisting extension while they viewed a visual display placed 50cm in front of them. This display contained 31 light-emitting diodes (LEDs) located behind a smoky-grey acrylic plate. The display consisted of a central, larger, red LED and vertical rows of smaller, yellow LEDs that were coupled to the output of the wrist position transducer so that each successively illuminated LED from the central lamp corresponded to an angular deflection of 1° from the central position. The subject's hand rested on an aluminum handle and the remainder of the forearm was supported by an arm rest. Each subject moved the handle and received an audible "click" if a movement of at least 5° was made in the appropriate direction. The behavioral tasks consisted of two trigger stimulus conditions in which movements were triggered by either a visual or one of three vibratory cues after the subject had maintained a centered wrist position for a period of time chosen randomly, but ranging between 0.5 and 2.0 sec. At the start of each trial, visual indicators, consisting of two additional LEDs placed in the upper left corner of the visual display, were presented which instructed each subject as to the direction of the required movement and the type of trigger stimuli that would be presented. Vibratory cues consisted of vibrating the handle with a low-amplitude sine wave (less than 100μ peak-to-peak) at either 27, 57 or 127 Hz. Visual cues consisted of adding or subtracting a DC voltage from the coupled wrist position signal, resulting in a shift in the illuminated lamp in the opposite direction from the requested movement by an amount equal to that required to re-center the

display . Flexion and extension movements were requested in alternating blocks of ten trials each. Vibratory and visual cues were randomly presented within blocks for a given vibratory stimulus frequency. Daily, three groups of 120 trials were collected. In each group, the vibratory stimulus frequency was held constant and the visually-cued trials randomly distributed. The total duration of these manipulations was about 20-30 min.

Primate Subjects

Each monkey was seated in a plexiglas primate chair and trained to make the same wrist flexion or extension movements described above, against or with a 0.07 Nm load assisting extension while they viewed a visual display placed 35cm in front of them. Each monkey received a fruit-juice reward for each correctly performed trial. In all other respects, the monkeys performed the same tasks as the human subjects.

Study #1 - Differences in Premovement Activity During Movements Made in Response to Visual vs. Vibratory Cues.

The records of 63 neurons in the sensorimotor cortices, for which each recording site was histologically approximated, were examined for this study. Table 1 shows the distribution of these data categorized by cortical location, type of significant premovement activity, activity onset before movement and comparative magnitude. Not all neurons had significant premovement activity changes under both stimulus conditions. For flexion trials, while 40 neurons changed activity before movement after either type of go-cue, 8 neurons showed significant changes only following vibratory cues, 1 only after the visual cue and 14 had changes that were less than the criterion. For extension trials, 37 had changes after both cues; 12 after only vibratory cues, 1 after only the visual cue and 13 had no significant change. Both groups of neurons, the 40 for flexion trials and the 37 for extension trials, included 5 neurons that where located in area 4 motor cortex. These five where excluded from the quantitative analysis of onset timing and premovement activity magnitude because this initial analysis focuses only on neurons located in the cortical regions that comprise classically defined SI.

Of the 35 SI neurons examined with respect to premovement activity before flexion movements, 13 had deep RFs located at the wrist, palm or fingers, 13 had small, punctate cutaneous RFs on the distal forearm or hand. The remaining nine movement related neurons either had no clear RF (NCRF) or were not tested. Of the 32 neurons included in the extension related population, 10 had deep RFs, 14 had cutaneous RFs and 8 were classified as NCRF or were not tested.

The records of the activity of all neurons examined in this study and the behavioral responses associated with trials during which they were recorded had two common features. First, the movements made in response to either vibratory or visual trigger stimuli were not qualitatively different upon visual inspection. The use of sustained vibration as a go-cue did not significantly alter the movement time, nor did it result in movements of different amplitude as compared to visually cued movements. Second, the records of the premovement activity in both visually and vibratory cued trials were characterized by abrupt changes in discharge rate rather than gradual increases or decreases in firing over a prolonged period prior to the onset of the movement.

TABLE 1

Flexion Trials

		Significant Premovement Activity				*Onset Before Movement*			*Comparative Magnitude*	
Location	N	N.C.	LS Only	Vib Only	LS&Vib	Vib before LS	LS before Vib	Same	LS>Vib	Vib>LS
Area 4	10	3	0	2	5	2/5	2/5	1/5	4/5	1/5
Area 3a	21	7	0	3	11	9/11	0/11	2/11	8/11	3/11
Area 3b	12	0	1	3	8	6/8	0/8	2/8	3/8	5/8
Area 1	17	4	0	0	13	8/13	2/13	3/13	6/10	4/10
Area 2	3	0	0	0	3	2/3	1/3	0/3	2/2	0/2
Totals	63	14	1	8	40	27/40	5/40	8/40	23/36	13/36

Extension Trials

		Significant Premovement Activity				*Onset Before Movement*			*Comparative Magnitude*	
Location	N	N.C.	LS Only	Vib Only	LS&Vib	Vib before LS	LS before Vib	Same	LS>Vib	Vib>LS
Area 4	10	2	0	3	5	3/5	2/5	0/5	3/5	2/5
Area 3a	21	4	1	4	12	6/12	6/12	0/12	8/12	4/12
Area 3b	12	3	0	2	7	5/7	2/7	0/7	5/6	1/6
Area 1	17	4	0	3	10	10/10	0/10	0/10	9/10	1/10
Area 2	3	0	0	0	3	3/3	0/3	0/3	3/3	0/3
Totals	63	13	1	12	37	27/37	10/37	0/37	28/36	8/36

Table 1. The distribution of recorded neurons by cortical areas, separated by movement direction and categorized by the occurrence of premovement activity, the onset of that activity before movements made in response to visual or vibratory cues and the comparison of the magnitude of the activity difference from background (see text). N.C.= no significant change, LS= Lamp Shift trials (visual cue), Vib= vibratory trials.

The changes in premovement activity were often quantitatively and occasionally qualitatively different under the two stimulus-cued conditions . Figure 1 illustrates the activity patterns of two SI cortical neurons recorded during task performance. Panels A. & C. depict the firing rate of an area 1 neuron that could be excited by passive extension of the wrist. On visual comparison, the activity occurring before movement onset appeared quite similar in both timing and magnitude when the vibratory cued trials in panel A. were compared to the visually cued trials, shown in panel C. When the records were analyzed with respect to the background activity that occurred while the animal maintained a steady, centered position against the load and the magnitude of the background activity was subtracted from the magnitude of the premovement change in activity, the changes in firing rate before movement during vibratory trials occurred at 170 msec before extension onset and had a mean discharge rate of 84.2 spikes per second over the background activity. In comparison, changes before movement during visually cued trials occurred 140 msec before extension onset and were 92.2 spikes per second greater than background. Panels B. & D. illustrate the records of another area 1 neuron that increased firing with passive flexion of the metacarpophalangeal joint of the second digit. This neuron showed a decrease in firing rate prior to movement onset for both visually and vibratory cued trials. The onset of the decrease preceding vibratory triggered extension movements occurred at 170 msec before movement onset while the decrease in visually cued trials began at 75 msec prior to movement. The decrease associated with vibratory trials had a mean of 12.8 spikes per second difference from background, whereas that for visual trials was 22.2 spikes per second. In both instances, the premovement activity changes associated with extension movements occurred earlier and were smaller for vibratory cued trials than for visually cued trials.

In some instances, the premovement changes in firing rate were dramatically different under the two stimulus triggered conditions. Neurons of this type, however, comprised only about 10% of the current population. In Figure 2, panels A. & C. depict the activity of an area 3a neuron during task performance. This neuron was sensitive to palpation of the medial side of the second digit near the region of the distal phalangeophalangeal joint where the corresponding lumbrical and palmar interosseous muscles have their attachment with the extensor expansion. This neuron responded to the onset of the 127 Hz vibratory stimulus at a latency of less than 15 msec, as seen in the left portion of the histogram in panel A. Although the vibration remained on until the animal moved, the firing rate decreased markedly from the rate associated with the vibration at 115 msec before movement onset. This type of activity pattern is reminiscent of the premovement suppression in firing rate seen in other SI neurons previously recorded during performance of this task [35,37]. In contrast, no visual stimulus related activity was seen during visually cued trials. However, at 145 msec before movement onset in visually cued trials, the activity of this neuron increased, peaking at movement onset. It should be noted that during the time when the discharge of this neuron is suppressed in vibratory cued trials, there was an increase in activity in visually cued trials. This suggests that the magnitude and sign of premovement activity in individual SI neurons may depend upon previous activity associated with other factors such as external stimuli capable of driving the neuron prior to the premovement interval.

Differences in premovement activity may be related to the proximity of external stimuli to the region of the body that subsequently will be moved. In figure 2, panels B. & D. illustrate the activity of an area 1 neuron that had a deep RF that could be excited by palpating a region near the median cubital fossa on the ventral surface of the forearm. The difference in premovement activity onset during vibratory and visually

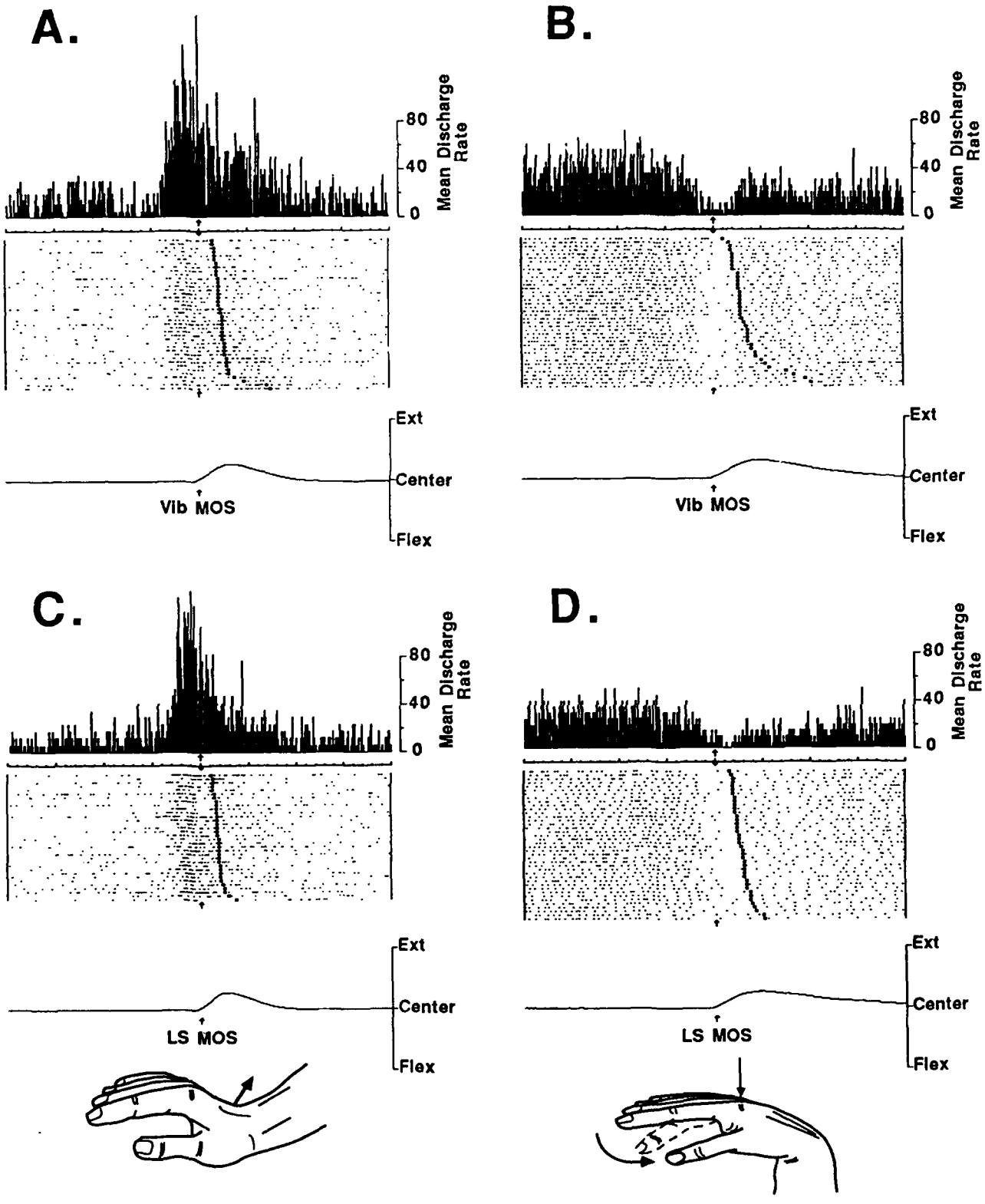


Figure 1. Rasters, histograms and average positional displacements of the handle for two SI neurons. In the raster displays, each row of dots represents one behavioral trial; each dot represents the output of the window discriminator and signifies a single neuronal spike. Each histogram represents the total activity the neuron during all similar trials, scaled for the number of trials and represented as the mean discharge rate in spikes per second. The trials are sorted and presented in order of increasing movement time (time to 5° deflection of the handle) from top to bottom. The position trace (lower portion of each panel) is the average of the handle displacement for each trial. All displays are centered on the onset of the movement which followed the type of go cue listed beneath the center of the position trace (Vib= vibratory-cued trials; LS= visually-cued trials; MOS= movement onset). The total period of the display is 2 sec.; each larger tick below the histograms represents 250 ms and each smaller one represents 50 ms. Bin widths are 10 ms. Panels A. & C. depict the activity of an area 1 neuron that responded to extension of the wrist outside the task. Panels B. & D. illustrate the activity of another area 1 that responded to passive flexion of the metacarpophalangeal joint of the second digit. (See text for description).

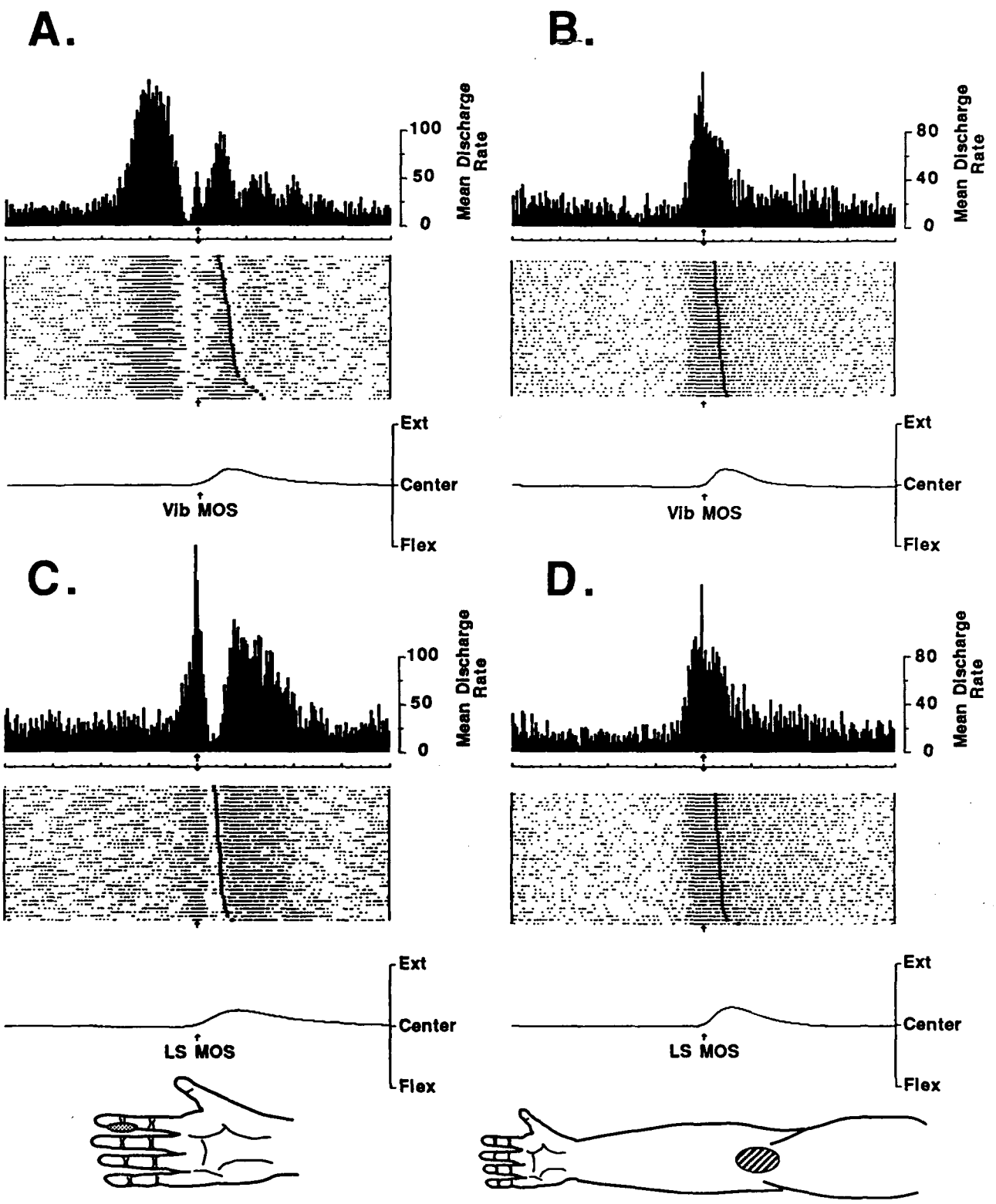


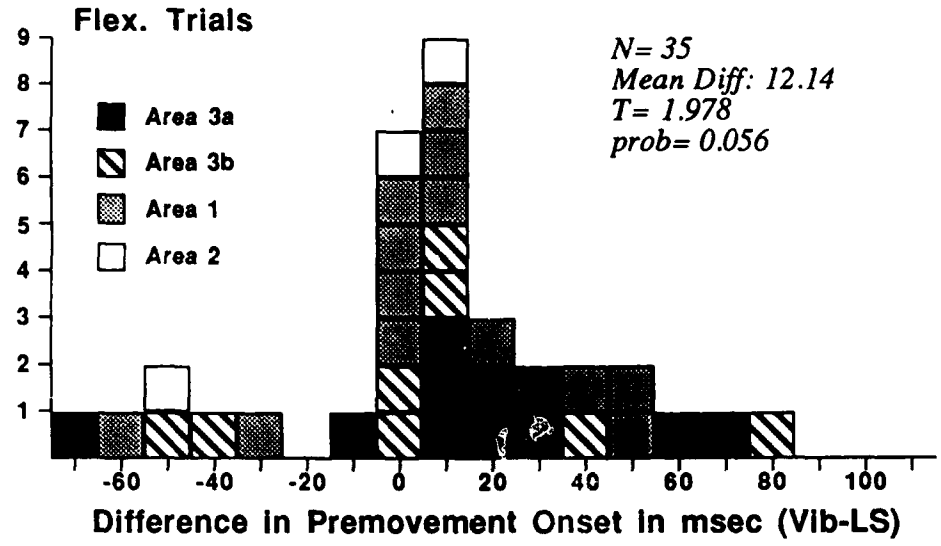
Figure 2. General description as in figure 1. Panels A. & C. represent the activity of an area 3a neuron that responded to palpation of the ulnar side of the second digit at the level of the distal phalangeophalageal joint. Note that in panel A., the 127 Hz vibratory stimulus-related activity to the left of the histogram is followed by a decrease in activity occurring before movement onset. In panel C., no change in activity is apparent until just prior to movement onset in these visually-cued trials. At this point there was an increase in activity. Panels B. & D. show the discharge pattern of an area 1 neuron that increased discharge during palpation of the ventral forearm near the median cubital fossa.

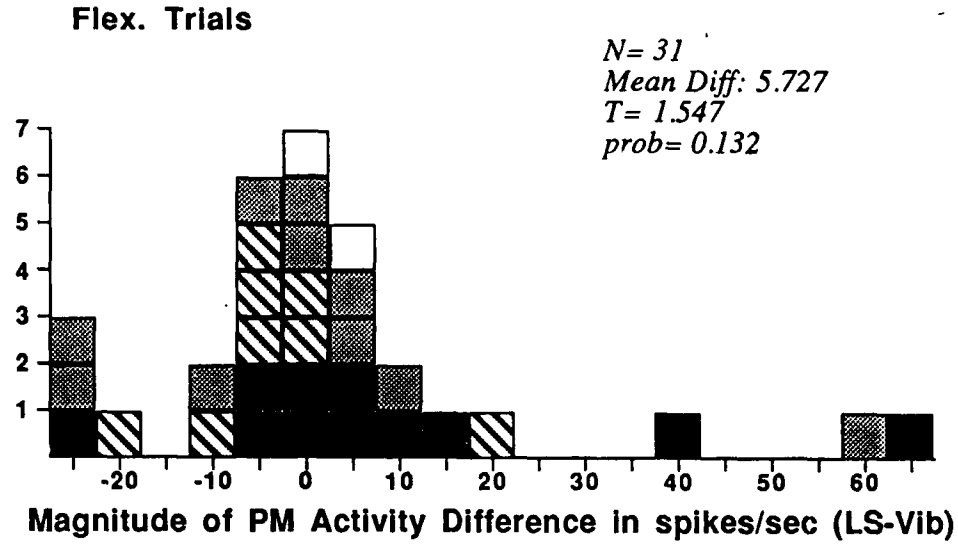
cued trials was 5 msec. The difference in mean discharge rate for the premovement activity under the two stimulus condition was less than 3 spikes per second. This suggests that under the two conditions the modulatory influences that result in premovement activation arrive at this neuron at approximately the same time and that they do not cause a difference in the activity pattern of this cell.

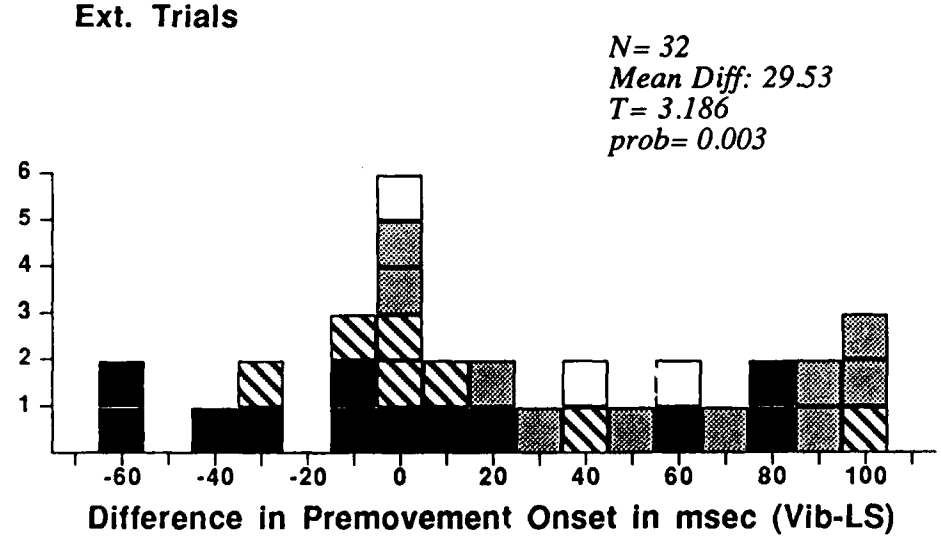
The onset of the premovement changes was measured for each SI neuron that exhibited premovement activity changes for both types of go-cue. Initially, we examined the differences in premovement activity onset and activity magnitude under the two stimulus cued conditions with respect to whether the neurons had deep or cutaneous RFs. The mean values of the onset time and the activity magnitude were not significant (probability> 0.01) using an unpaired t-test and grouping these variables by type of receptive field. The Bartlett test for homogeneity of group variances was not significant for the onset times, yet was significant for the magnitude of activity changes (probability<0.01). This suggests that while the means for the premovement activity magnitudes were not different, the activity of the populations of neurons with deep as compared to cutaneous RFs were different under the two stimulus cued conditions. In general, there was a tendency for neurons with deep receptive fields to have greater differences in the premovement magnitudes when compared with neurons having cutaneous RFs. There was no clear tendency toward greater differences in onset timing of the premovement activity during visually and vibratory cued trials when cells with deep RFs were compared to neurons having cutaneous RFs. Based on these observations, and because of the small sample size, the data from all SI neurons was therefore pooled to examine the trends in premovement activity differences and timing.

As can be seen in Figure 3, the onset of the premovement activity changes during vibratory cued trials for the SI neurons taken as a whole often preceded those calculated for the corresponding visually cued trials. The magnitude of the premovement activity changes during visually-cued trials for these same neurons tended to have a greater deviation from the background activity than did those changes occurring following vibratory cues. Measurements of the mean difference in premovement activity onset for the SI neurons indicated that the onset of activity in vibratory-cued trials led that in visually-cued trials by 12.1 msec and 29.5 msec for flexion and extension trials, respectively. In comparison, the magnitude of the activity was greater for visually-cued trials by 5.73 and 5.95 spikes per second in mean discharge rate for flexion and extension trials, respectively. By our criterion of significance, the mean difference in the onset and the magnitude of the premovement activity recorded for these neurons during trials resulting in extension movements (with the load) were significantly different. The calculated difference values during flexion movement trials (against the load) were not significant (p>0.01).

Despite the small size of the current population of histologically confirmed SI neurons, differences have been observed in the premovement activity onset and magnitude recorded during vibratory as compared with visually cued trials. Premovement activity changes during trials triggered by vibratory cues tend to occur earlier than changes associated with the same movements made in response to a visual cue. The mean onset difference in activity was significant for extension movements and approached a significant level for flexion movements. The magnitude of the premovement activity changes that do occur tends to be different before movements made in response to visual cues as compared to the same movements made following vibratory stimuli. The mean discharge rates of the premovement activity recorded during visually cued extension movements was significantly greater than for the corresponding movements made following vibration. The magnitude of the flexion premovement activation approached significance as well.







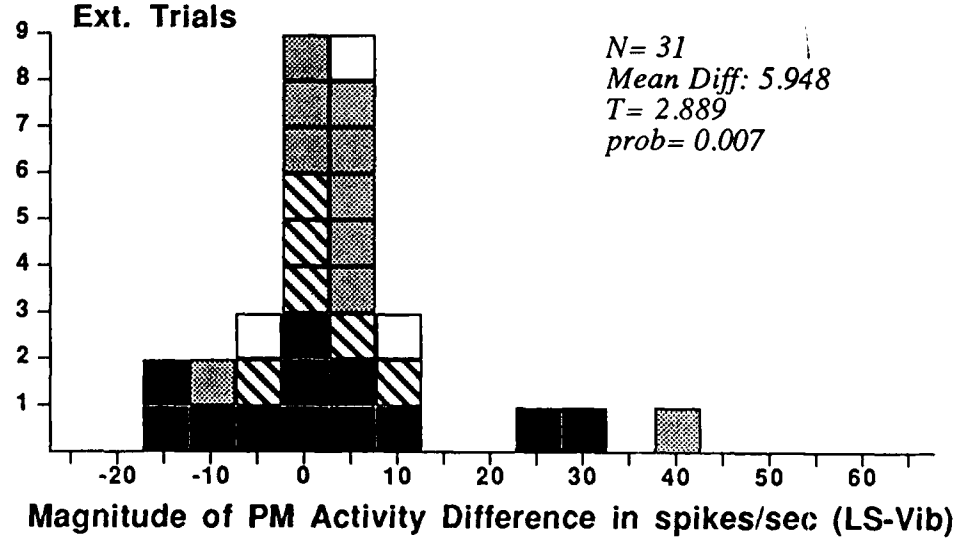


Figure 3. The differences in the onset and magnitude of the premovement activity for all SI neurons that show significant activity changes for both visual and vibratory-cued trials. Values for each neuron are coded by the cortical area in which each neuron was located. For the onset plots, the onset of the premovement activity following the visual go-cue was subtracted from that for vibratory-cued trials for each neuron. For the magnitude plots, the magnitude of the activity over or below background for vibratory-cued trials was subtracted from that for the visually cued trials. Paired t-tests were done for the values used to construct each plot. The mean difference, the t-statistic and the probability of the mean difference being significantly different from zero are listed in the right of each panel.

The comparative differences in the magnitude of premovement activity in some SI neurons may be related to the current state of activity. One current observation is that the most profound differences occur when a given SI neuron has previously shown some response to the presence of a vibratory stimulus in or near the neuron's receptive field. To investigate the relationship between the amount of peripheral stimulus related discharge and the subsequent premovement activity, another population of vibratory responsive neurons has been analyzed. The results from this analysis indicate that the magnitude of the premovement activity changes are inversely proportional to the amount of a neuron's vibratory response that occurs before the premovement activity that in clearly associated with a time prior to movement onset (see below). The onset of these changes, however, remains relatively constant.

The differences in timing and magnitude may not be as marked when a neuron does not respond to one particular frequency of vibration or if the receptive field is some distance from the site of stimulation. As examples, compare the records illustrated in Figure 1 with those shown in Figure 2, panels B. & D. The absence of magnitude and timing differences under the two conditions, for neurons with RFs at a distance from both the vibratory stimulation site and the region of the forelimb to be moved (e.g., Figure 2, panels B. and D.), is in keeping with findings reported by other studies in which it was found that the perception of a peripheral stimulus by human subjects was more profoundly attenuated if the location of that stimulus was nearest the part of the forelimb that was subsequently moved. If premovement activity changes in SI neurons are actually neural correlates of the sensitivity changes that precede active movement, then the magnitude of the differences in premovement activity under the two conditions would be expected to decrease with increasing distance of a neuron's RF from the stimulation and movement sites, as has been observed in this study.

Underlying the interpretation of the observations made in this continuing study is one crucial assumption. Vibratory stimuli have been shown to not only excite peripheral cutaneous receptors, but also have the capacity to excite and, under some conditions, entrain the firing patterns of group Ia muscle afferents. Both of these types of peripheral receptors presumably play a crucial role in informing the nervous system of the current state of the limb in space and provide information about the initiation and execution of active movement. If vibratory stimuli initially provide the cue to signal that a movement may begin and are left on until the animal moves the stimulated limb, these same stimuli may actually "interfere" with the nervous system's ability to accurately monitor the impending movement, because they activate the very receptors that would be used in this monitoring. If this is the case, then under conditions where the movement triggering stimulus does not activate cutaneous or deep receptors (e.g., a visual stimulus), the premovement activity would be expected to be different from that which occurs when the peripheral receptors were previously activated by a stimulus. Indeed, this is what has been observed in the present study. As a consequence of potential interference by vibratory stimuli, it might be expected that performance, as measured by the time necessary make a 5° movement, might be longer during vibratory as compared with visual trials. Our initial assessment of the data obtained under these experimental conditions suggests that this is not the case.

The results of these experiments suggest at least two mechanisms that might account for the differences in timing and magnitude of the premovement activity that was observed before monkeys made wrist movement in response to ongoing vibratory or visual cues. First, ongoing vibratory stimulation in the periphery may, in some way, alter the responsiveness of SI neurons so that centrally generated modulatory

influences are less effective in cause changes in the firing rates of SI neurons before movement. Alternatively, the presence of vibration may alter the nature of the centrally generated influences themselves, so that the signals arriving at SI prior to movement are different under the two conditions.

While the evidence is indirect, the results of this study favor the later possible mechanism. If the presence of vibration in the periphery causes a change in responsiveness of SI neurons to central inputs, then two things might be expected. First, it would be expected that the magnitude of the premovement activity observed following vibratory go-cues would be diminished or increased from that observed during trials in which visual cues triggered the movement sequence. This, of course, was observed in the present study. If the centrally generated modulatory signals are unaffected while the responsiveness of SI neurons to central inputs is altered, then it might be predicted that for SI neurons where premovement activity changes are observed, the onset of this activity should be at the same time under both stimulus cued conditions regardless of the presence or absence of ongoing vibratory stimulation in the periphery. On the contrary, the onset of premovement activity occurs earlier following vibratory go-cues than following visual go-cues. Second, for SI neurons of the type illustrated in Figure 2, panels A. & C., a general change in responsiveness of SI neurons would not necessarily account for the qualitatively different premovement responses that are sometimes observed. In this case, prior to movement in response to the vibratory cue, firing rate was dramatically decreased, whereas prior to the same movement in response to a visual cue, this neuron exhibited a profound increase in activity at approximately the same time that it decreased activity during vibratory cued trials. The onset of this premovement activity under both conditions was early enough to suggest that the change in firing rate arose for centrally generated influences rather than from additional afference resulting from the increase in muscle tension before any detectable change in limb position. It is possible that the differences in the onset times of the premovement activity could partially be accounted for by the differences in the processing time of somatic and visual information. It has been shown that the onset of cortical activity following the presentation of visual stimuli lags that for the presentation of somatic stimuli by tens of milliseconds and that human and primate reaction times for a movement made in response to visual stimuli are longer than those for the same movement made in response to somatic stimuli. Despite this inherent difference in information processing times, the onset of premovement activity changes to either stimulus modality, seen in the current study, are temporally correlated with movement onset and not with some fixed time after stimulus onset. Taken together, these observations suggest that the centrally generated modulatory influences that arrive at SI prior to movement onset may be different depending upon the type of sensory stimulus which was used to signal that a movement may begin and are still present during the initiation and execution of that movement.

This hypothesis is readily testable. As an alternative to visual cues, auditory stimuli could be used to trigger wrist movement. We would predict that the premovement activity associated with auditory cued trials would be comparable to visually cued trials. Presuming that the requirements for monitoring limb position influence the nature of premovement activity in SI neurons, targeted or tracking movements of the wrist will be employed rather than the "free-ranging" movements used in this study. We predict that the increased precision required for these movements would also require more precise limb position monitoring and will result in increased differences in the amplitude of premovement activity when visually cued trials are compared to those triggered by vibration. Finally, the duration of the vibratory cueing stimuli could be shorten to test whether the differences in premovement activity amplitude are dependent

upon whether the vibration is still present as the animal initiates the movement sequence. Our hypothesis would predict that with vibratory stimuli of short duration, the amplitude of the premovement activity would be similar to trials triggered by visual cues since the vibratory stimulus would no longer be present to interfere with the monitoring of wrist position and muscle activity.

The site at which centrally generated modulatory influences may be exerted is unclear. We have previously argued that these inputs to the somatosensory system are possibly from corticocortical connections with area 4 because neurons in the regions that receive direct connections from motor cortex (areas 3a,1 and 2) exhibit the most profound premovement activity changes. In an earlier study we found that changes in premovement activity changes in vibratory responsive and non-vibratory responsive area 3b neurons are rare. The results of the present study suggest that at least some area 3b neurons do show premovement activity changes under the current task conditions. The current sample size is small, yet we have observed that the differences in magnitude of premovement activity changes for area 3b neurons under the two conditions tended to be distributed over a smaller range than in the other regions which comprise SI.

The results of this study suggest that the activity of SI cortical neurons during the initiation and execution of active movement of the stimulated portion of the forelimb is dependent upon the type of external stimulus used to signal that a movement sequence may begin. They may be interpreted to imply that centrally generated modulatory influences, thought to reflect a corollary discharge of the initiation of the movement itself, may be different depending upon the location of the cue stimulus with respect to an SI neuron's RF and its relationship to the part of the body that will be moved. Studies of this sort may provide important insights into the processing of sensory information by the somatosensory cortex when that information is initially instructive but may also interfere with the monitoring of the state of the forelimb and its position in space. Further investigations were conducted to determine the relationship between an SI neuron's capacity to respond to a peripheral vibratory stimulus and the degree to which the neuron's activity is altered prior to movement onset.

Study #2 - The Relationship Between Premovement Activity and Vibratory Responsiveness of Primary Somatosensory Cortical Neurons.

As a consequence of the analysis that was conducted for Study #1, we examined the records of an additional 55 histologically confirmed neurons for this second study. These neurons all exhibited 1) a short latency (<50msec) change in firing rate that was associated with the onset of the vibratory go-cues and 2) showed an additional changes in activity that was time-locked with and preceded the onset of flexion or extension movements of the wrist. Forty-seven neurons were analyzed for their activity during flexion trials and 52 neurons were examined for their changes in firing rate during extension trials. In all instances, the premovement activity was clearly dissociated from each neuron's response to vibratory stimulus onset by at least 80 msec.

The mean background activity, the mean vibratory response and the mean premovement activity of each neuron was calculated in a manner similar to the calculations described in Study #1. Briefly, background activity was measured during the time when the animals held a steady position against the loaded handle with not vibration present. The mean vibratory activity was defined as the first change in firing rate that was at least 50% above or below the background rate for at least 30 msec. The

premovement activity was calculated as the change in activity that was not stimulus-related, at least 50% above or below the background rate for at least 30 msec, that occurred before movement onset and that was separate from the stimulus-related response by at least 80 msec. Both the response magnitude and the premovement activity magnitude were calculated by subtracting the mean background activity from the firing rate of the neurons during the stimulus-response period or the premovement activity period.

The question to be answered was "what is the relationship between the magnitude of the vibratory response and the magnitude of the premovement activity"? Several hypotheses were tested by examining this relationship. First, it is possible that SI neurons respond to vibratory stimuli and then show no further change in firing rate until the animal moves. Many neurons of this type were available from our data pool but were excluded from this analysis because, by definition, they would then have no discernable premovement activity change. Second, SI neurons might have stimulus-related responses as well as premovement activity changes, yet there might be no relationship between the magnitude of the stimulus response and that of the premovement activity. This would suggest that these two types of activity are not related in any simply demonstratable form. Finally, increased stimulus sensitivity as measured by increased stimulus-related activity may be correlated with either increased or decreased premovement activity as measured by the magnitude by which this activity deviates from the measured background activity.

Figure 4. illustrates the distributions of the times at which premovement activity changes were observed in the population of SI neurons under analysis. For both flexion and extension movements, premovement activity changes were most often observed between 40-190msec before movement onset. The outliners in these graphs (time>190msec) were recorded during one day of trials in which the animal made exceptionally slow movements in response to the vibratory trigger stimuli.

As stated above, the magnitude of the vibratory response (VR) and the magnitude of the premovement activity (PM) were calculated by subtracting the mean firing rate during these corresponding periods from the calculated background activity. Figure 5 plots PM as a function of VR for both flexion and extension trials. Both sets of data resulted in graphs in which the initial points obtained at relatively low VR and PM form roughly linear clusters. In both instances, as vibratory responsiveness increased, so did the PM, but the proportional increases in PM appeared to be less with increasing VR. Two simple functions were fit to the data in both graphs to determine the best-fit model which could describe the data. A simple linear regression of the data was made using the equation:

$$(1) \qquad PM = \text{constant} + \text{coefficient} \times VR$$

This resulted in multiple regression values of 0.665 and 0.832 for flexion and extension trials, respectively, indicating the relative fit of the model equation to the actual data. The coefficients for both linear equations are shown in figure 5 were significantly different from zero ($p<0.001$) as was the constant for the extension model. The constant for the flexion model was not statistically different from zero ($p=0.767$).

Next, a 2nd order polynomial model was fit to the data. This type of model was used to determine if the data showed a systematic increase or decrease in the proportional relationship between VR and PM with increasing VR. The equation:

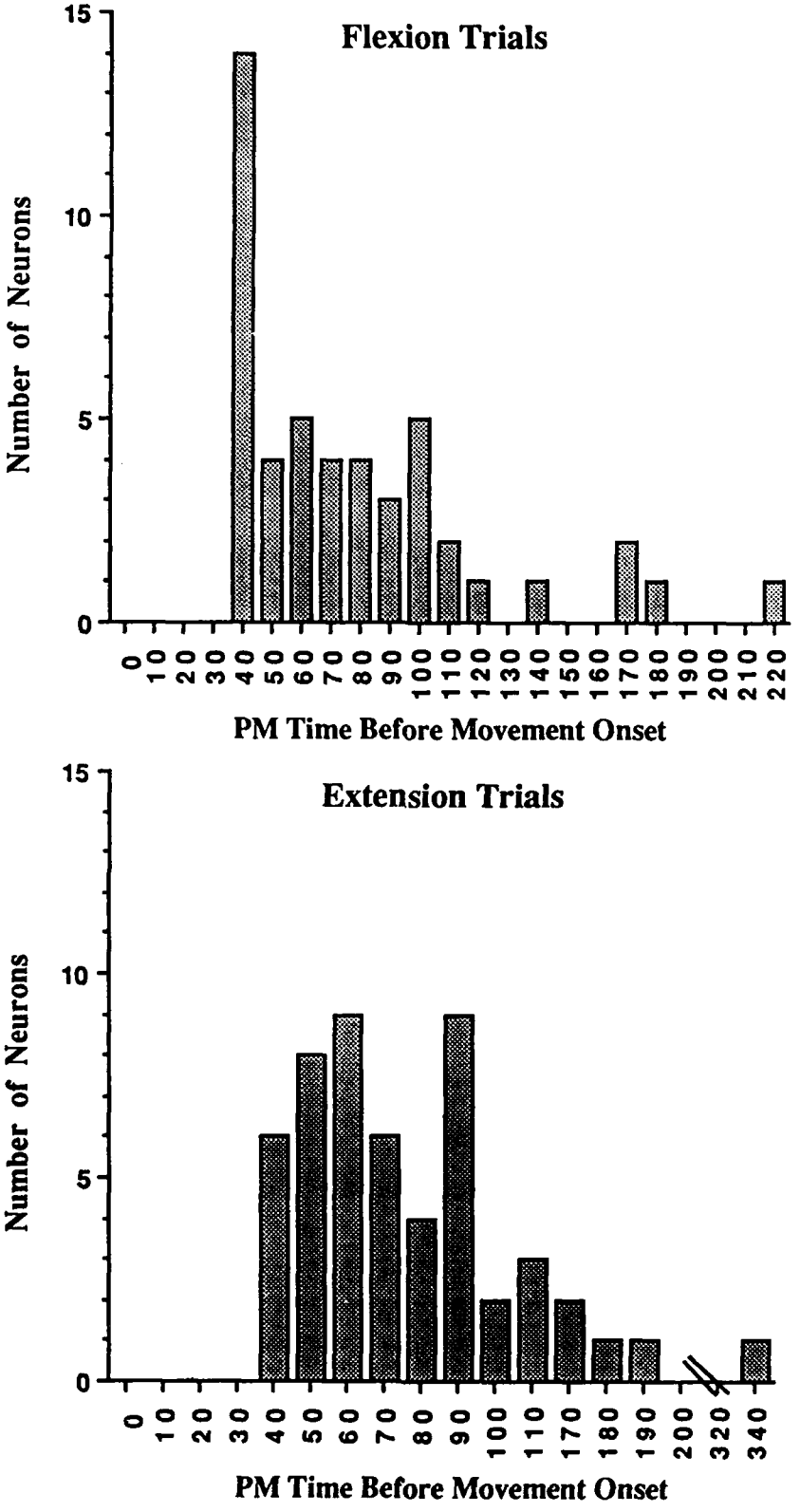
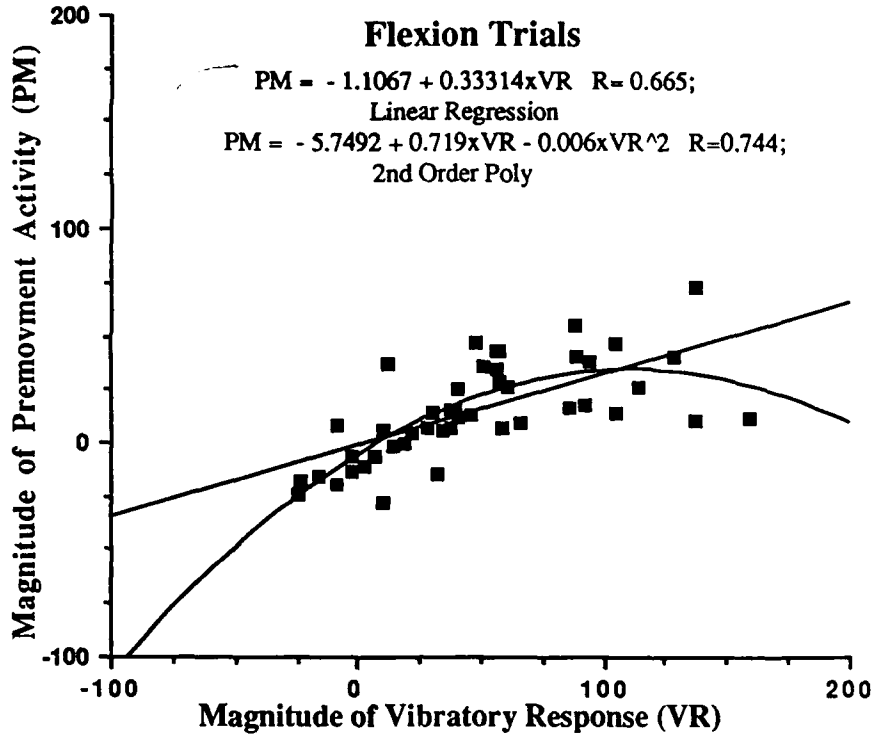


Figure 4. Distribution of the times before movement onset at which vibratory responsive neurons exhibited pre-movement activity changes prior to flexion or extension movement of the wrist.



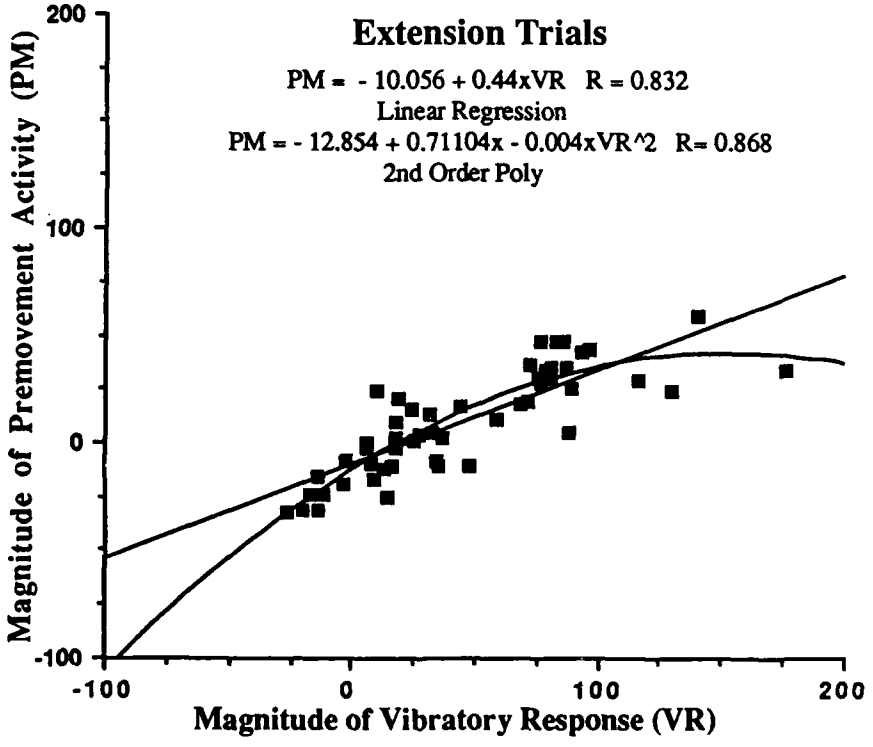


Figure 5. The magnitude of the premovement activity of each neuron analyzed plotted against the magnitude of the vibratory response. Both values were derived by substracting the background activity from the mean activity during the two sampling periods. The straight line denotes the best fit linear regression of the data (PM activity= constant+coeff x VR). The curved line indicates the best fit polynomial (PM= constant+coeff(1) x VR + coeff(2) x VR^2). The data was best fit by a 2nd Order polynomial and higher order polynomials yielded the same regression coefficient.

$$(2) \quad PM = \text{constant} + \text{coefficient}_1 \times VR + \text{coefficient}_2 \times VR^2$$

was fit to both data populations. For both flexion and extension trials, the multiple regression values were higher for this model than for the simple linear model, indicating that this type of model resulted in a better fit of the actual data. Higher order polynomials and exponentials equations did not result in an approved fit.

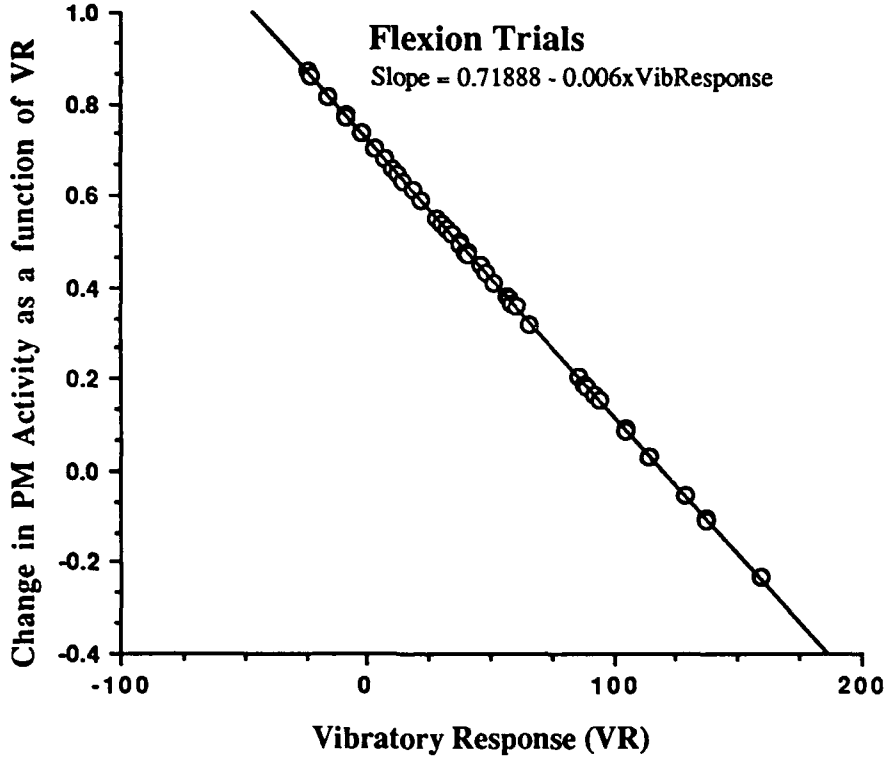
This type of model and its fit suggests that as VR increases, so does PM, yet the proportional increase in PM is less as VR increases. To illustrate this, equation 2 was differentiated to yield the slope of the best-fit model of the data, resulting in the equation:

$$(3) \quad \text{Predicted Slope} = \text{coefficient}_1 - (2 \times (\text{coefficient}_2 \times VR))$$

This predicted slope of the function described in equation 2 is plotted against the actual VR data point in figure 6. This figure illustrates that as VR increases, the proportional increase in PM becomes less.These observations suggest for SI neurons that have both vibratory responses and premovement activity changes, the more robust the sensory response, the less likely these neurons are to show robust premovement responses.

Several relationships between VR and PM might have been expected. First, the VR might have been sustained from the time of stimulus onset to movement onset. This would result in no discernable PM. As stated above, many SI neurons of this type were observed and were excluded from this data analysis because it would be impossible to determine the VR-PM relationship from these neurons. Neurons of this type are commonly found in area 3b of SI, yet are rare in the other cortical regions that comprise SI (areas 3a, 1 and 2). Secondly, the PM might be additive to a sustained VR. Thus would result in PM for those neurons which was significantly greater than the VR, since both values are calculated by taking the mean firing rate minus the background activity. No neurons showing this response profile were observed in the records of neurons taken from three different monkeys so we feel relatively sure that if this type neuron exists, it is relatively rare. Finally, SI neurons may adapt quickly to the VR, so that after the initial burst of activity associated with stimulus onset, their firing rates return to near background levels during the time after the signals associated with the go-cue have been received and the animals are initiating the movement. Then, prior to movement onset, the SI neurons once again show activity changes, but these are correlated with some time prior to the onset of movement, rather than to the presentation of the external stimulus.

Given the attractiveness of this third possibility, two mechanisms might account for our data. First, SI neurons may adapt quickly to external stimuli either by pre-cortical mechanisms, such as the inherent properties of the sensory receptors themselves or due to inhibit of sensory transmission in the ascending somatosensory pathways before the sensory signals reach cortical levels. It has been shown that both slowly and rapidly adapting afferent fibers are present in peripheral nerves. It has, however, also been suggested that cortical neurons which adapt quickly to the presentation of sensory stimuli may receive input from slowly adapting afferents, yet also be inhibited by centrally generated inputs. These central inhibitory inputs could account for the return of the firing rate to near background levels after the initial burst of activity associated with stimulus onset. Presuming this is the case, the observed PM might be the



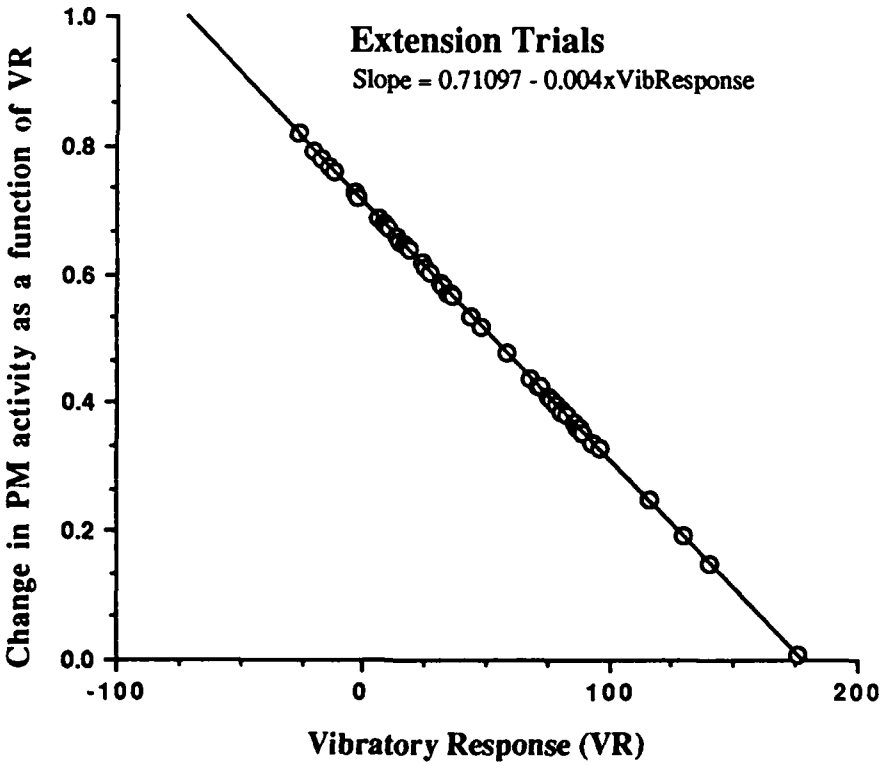


Figure 6. The predicted relationship of the magnitude of premovement activity as a function of vibratory responsiveness of SI neurons. The best fit function of VR by PM (PM= constant+coeff(1) x VR + coeff(2) x VR^2) was differentiated (Predicted Slope= coeff(1) + 2 x coeff(2) x VR) to give the predicted change in the magnitude of the premovement activty as a function of increasing vibratory responsiveness. As vibratory responsiveness increases, the magnitude of the premovement activity difference from the background decreases, supporting the hypothesis that the more responsive a neuron is to external stimuli, the more likely that neuron's premovement activity will be suppressed.

result of disinhibition of SI neurons at some time before movement onset. If this were strictly the case, then we might except that the PM would be the result of this disinhibition and that since the vibratory stimulus is still present, the PM should be of approximately the same magnitude as the initial burst associated with stimulus onset. This might be the case for cell in which the VR and the PM are relatively small because in those instances, the ratio of the PM to the VR approaches 1.0. However, when neurons exhibit more robust VR, the ratio of the PM to the VR decreases, suggesting that the PM is not simply the result of the SI neuron being capable of responding, once again, to the existent vibratory stimulus. This decreasing ratio suggests that there are two separate instances during which SI neurons are responsive to modulatory inputs. The first is that associated with external stimulation; the second is prior to movement.

It is possible that, in some instances, the PM activity is the result of peripheral rather than centrally generated modulatory influences. Many of the analyzed SI neurons exhibit PM less than 70msec before movement onset. We have previously shown that the muscles involved in this task become active before the onset of movement and that the transmission of the signals resulting from muscular activity would be expected to reach the cortex no earlier than this time. This does not preclude the possibility that the PM activity of these analyzed neurons results from central rather than peripheral inputs. The majority of the studied neurons had cutaneous receptive field and did not respond to palpation of muscles when done outside the task.

Until we have histologically confirmed the remaining neurons which could be added to this analysis, we can only suggest possible relationships between VR and PM. Yet, the results of the first study, taken together with the observations presented above, suggest that the PM activity seen in SI neurons is effected not only by the type of trigger stimulus used to signal the animal that a movement may begin, but also that the PM activity varies as a function of how robustly the SI neurons respond to the trigger stimulus that is used.

Study #3 - Differences in Reaction Times When Humans and Monkeys Make Hand Movements in Response to Visual vs. Vibratory Cues.

The electrophysiological studies conducted with primates have shown that identical movements made by monkeys in responses to different type of sensory go-cues are correlated with different types of cortical neuronal activity. We have set forth hypotheses as to the mechanisms that might account for this differential neuronal discharge in our attempt to better understand the neuronal basis for the sensory contribution of motor control. Making use of this information for more practical applications, it is necessary to know whether the initiation and execution of identical movements in response to differing sensory cues also differs. To determine whether there is any advantages to humans subjects in using one type of sensory cue versus another to signal that a desired movement may begin, we have compared the time it takes for human or monkey subjects to move their hands in response to vibratory, a compared with visual cues. The time from stimulus onset to the first detectable change in wrist position (reaction time; RT) was measured for two monkeys and eight human subjects that were trained to make wrist movements as quickly as possible in response to both vibratory and visual go cues. It has been previously shown that the capacity for vibratory and visual detection and discrimination is similar for humans as compared with monkeys. If this holds true for our behavioral paradigm, then we can generalize from one species to the another. This presents to benefits for our work. First, we can infer what the mechanisms for sensory

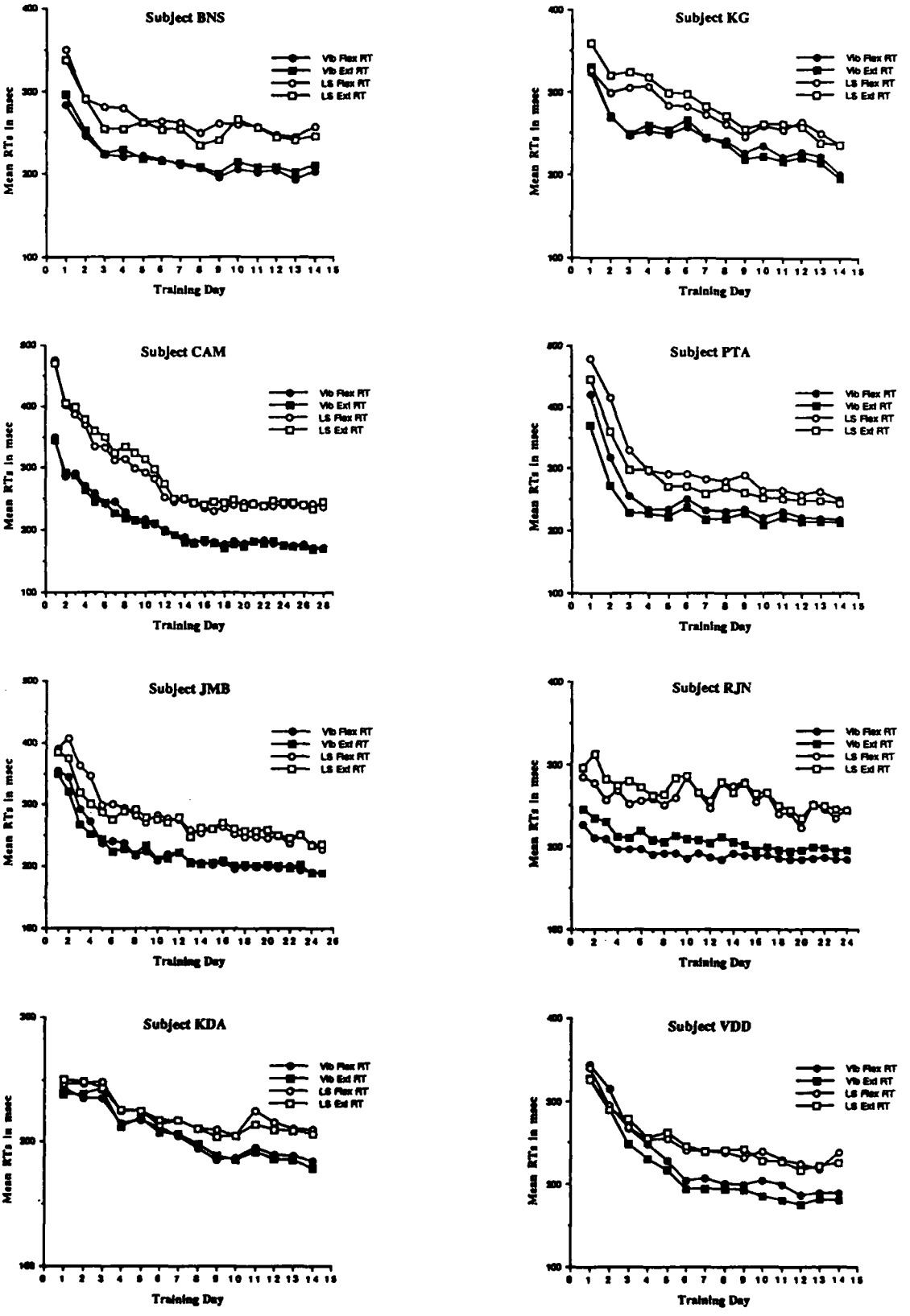


Figure 7. The reaction times of eight human subjects who performed wrist flexion and extension movements in response to visual or vibratory go-cues. Closed symbols represent vibratory trials; closed symbols depict visually-cued trials. In all cases, movements made in response to vibratory stimuli were made more quickly than the corresponding visually-triggered movements.

processing during the initiation and execution might be in humans from the monkey neurophysiological studies. Second, when training monkeys to perform complex tasks, we can first determine the proper parameters during human psychophysical studies, and then use the same parameters during neurophysiological recording in monkeys.

TABLE 2

Mean Daily RTs for 8 Human Subjects

Training Day	LS Flex	VIB Flex	LS Ext	VIB Ext
1	358.14	318.20	361.28	312.24
2	324.95	278.04	328.46	271.26
3	299.69	252.60	304.63	247.06
4	288.39	238.54	292.85	235.98
5	280.45	230.39	274.99	228.80
6	272.50	227.34	272.40	225.70
7	266.08	221.30	267.26	217.11
8	264.51	213.79	260.53	212.33
9	260.70	208.88	258.29	211.25
10	261.04	207.93	260.31	205.66
11	254.98	208.53	256.70	206.09
12	248.09	204.58	247.85	203.55
13	241.80	199.38	245.58	200.95
14	241.89	197.64	245.51	195.73

Mean Daily RTs for 3 Human Subjects Studied for 24 Days

Training Day	LS Flex	VIB Flex	LS Ext	VIB Ext
1	382.93	310.34	383.00	312.83
2	361.37	280.10	363.60	282.40
3	335.37	264.47	333.67	261.60
4	328.37	246.60	318.37	242.83
5	295.23	231.13	308.40	233.50
6	296.97	226.37	299.13	229.37
7	288.40	224.63	291.80	220.60
8	282.27	212.43	296.97	214.23
9	276.10	210.43	295.37	220.83
10	285.67	203.70	292.10	209.50
11	275.33	206.97	277.73	210.30
12	258.33	202.73	269.53	207.77
13	260.33	194.70	259.13	203.27
14	258.63	195.30	259.70	196.47
15	260.90	190.83	260.57	195.73
16	251.77	191.00	258.57	195.93
17	249.30	187.73	257.50	192.67
18	240.90	186.73	250.13	189.07
19	242.67	187.97	250.30	190.87
20	237.27	186.87	243.40	190.20
21	248.23	188.13	247.97	194.13
22	240.67	190.37	245.03	190.73
23	241.17	185.90	247.70	193.30
24	240.27	183.13	240.77	186.63

Table 2. Above: The averaged mean daily reaction times of 8 human subjects who made flexion (Flex) or extension (Ext) movement in response to vibratory (VIB) of visual (LS) go-cues. Below: The RTs of three subjects studied for 24 days. Noted that while the final averages for the LS trials are the same in the two groups, the RTs for vibratory trials improved by approximately 10 msec with further training.

Figure 7 shows the performance of eight human subjects as they made flexion and extension wrist movements in response to visual (LS= Lamp Shift) and vibratory (Vib) go-cues. Each subject made movements in response to vibratory cues more quickly than when the same movements were requested using a visual cue. Table 2 lists the mean reaction times for each cue-movement pair as a function of the training day for all eight subjects and, separately, for three of the subjects that were studied for a longer period of time. Figure 8 depicts these result graphically and indicates the days during which the differences in the mean reaction times for similar movements made in response to visual and vibratory cues were significantly different as indicate by a *paired t-test.* At the end of the normal 14 day training period, vibratory as compared with visual trial RTs were 44.25 and 49.79 msec faster for flexion and extension trials, respectively. For the three subjects studied for at least 24 days, the final RTs for vibratory trials versus visual trials were only slightly different than the values for subjects tested for only 14 days, being 54.13 and 57.13 msec faster on vibratory trials for flexion and extension movement, respectively.

Figure 9. illustrates the daily differences in mean RTs for both populations of subjects, in panel A. In panel B., the daily mean differences in RTs for one of the monkeys are shown. With the exception of one of the training days, a reasonably consistent difference in RTs for the same movements made in response to the two types of go-cues was maintained throughout. In panel C., the RTs for all 160 days of training are shown, illustrating the consistent 70-80 msec difference in favor of vibratory trials with which this animal performed the task and the relationship between RTs for the same movements cued by different trigger stimuli. Results of another extensively studied monkey were nearly identical and are not shown.

We sought to determine what factors might set the subjects which were studied for the longer period of time apart from the remainder. The only consistent differences between these two populations were that the smaller population for subjects were slightly older than the others (mean age 33.3 years as compared with 26.2 years) and that the three individuals in the smaller group were previously familiar with the task before they were asked to perform it.

One general trend also emerged for the examination of the data. Subjects tended to begin training, with a few exceptions, have reaction times that were quite high. Within the first few days of training, these times decreased until the RTs for visually cued trials reached a plateau. However, vibratory reaction times showed addition improvement with continued training. This resulted in an approximately 50-60 msec difference in comparative RTs, in favor of trials initiated in response to vibratory cues. Since the mean reactions times for visually cued trials averaged approximately 240 msec, this represents on the order of a 20% improvement in the time to movement when vibratory cues are used in this simple task.

It remains to be determined whether a similar improvement can be maintained during the performance of more complex tasks. In the continuation of this research, we will be employing more complex targeted movement and tracking tasks, as well as attempting to determine if and at what crucial period in the movement cycle, a request for hand movement can be overriden. This determination could prove to be of great benefit if the task requirements include not only the fastest response to external events but also the necessity to abort a movement based on changing environmental conditions.

It is clear that movements made in response to vibratory cues have the advantage of being executed more quickly. There may be other factors which make the presentation of information by vibratory cues desirable. In many tasks which involved the control of devices by hand movements, the subjects are already preoccupied with the visual and auditory environment. Additional visual cues may distract from

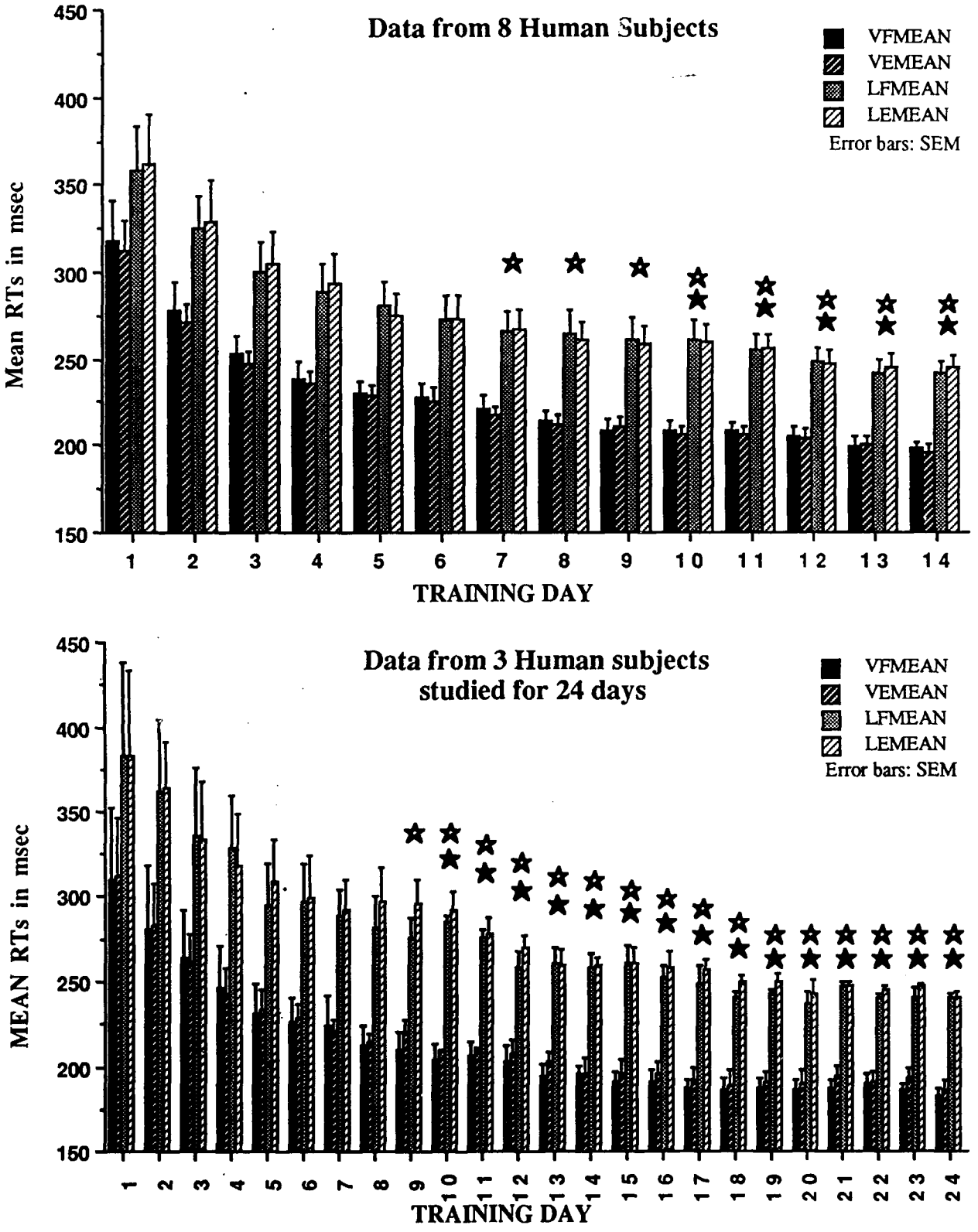


Figure 8. The daily mean reaction times of human subjects who performed the tasks. Above: The pooled mean reaction times of all eight subjects. Below: The data from three of those subjects who were studied for at least 24 days. ★ for Flexion; ★ for Extension = days during which the mean RTs for similiar movements made in response to vibratory vs. visual cues were significantly different ($p<=0.001$ for eight subjects; $p<=0.01$ for the three subjects).

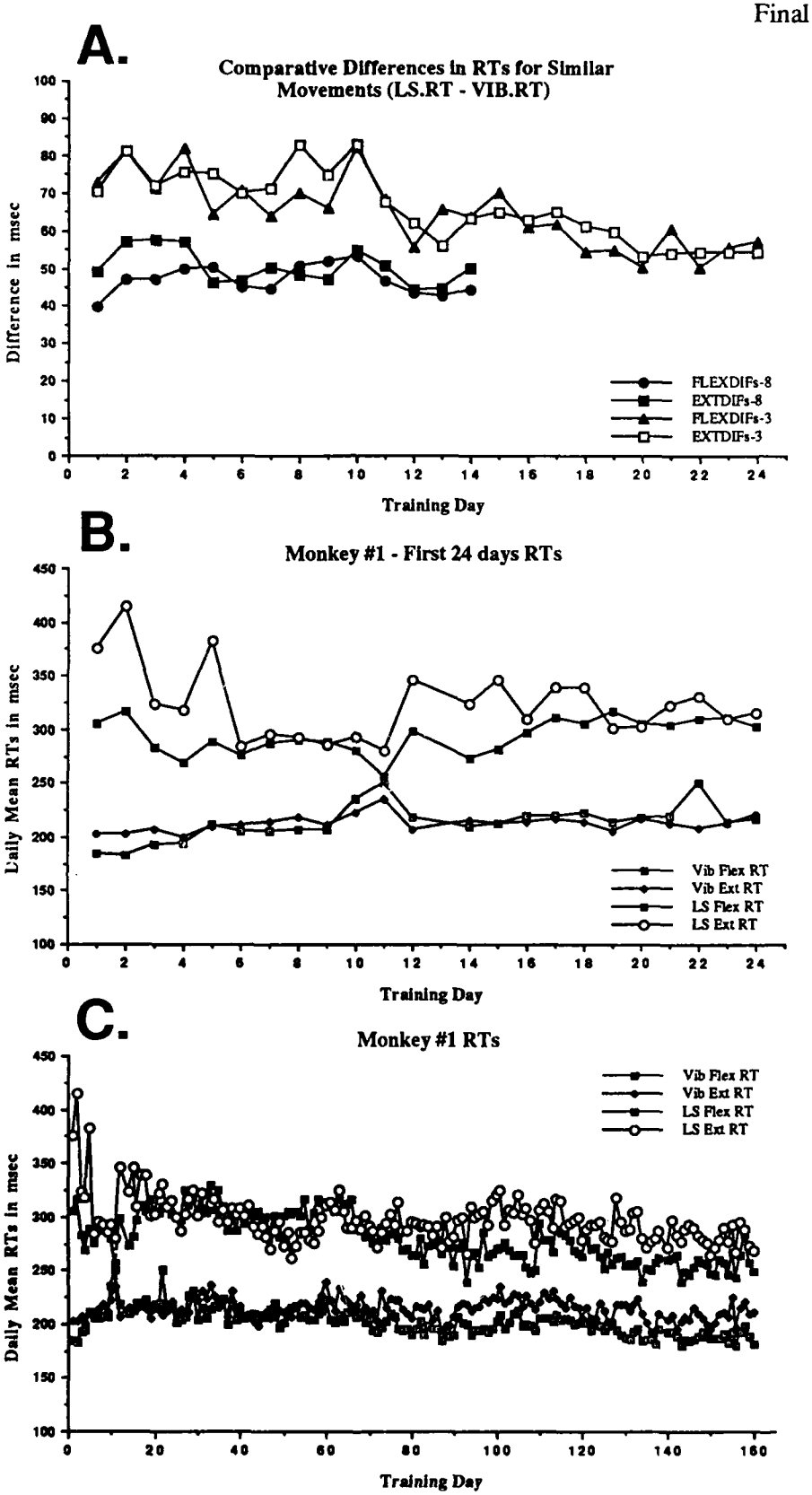


Figure 9. A: The difference in daily mean reaction times (RTs) for all eight subjects studied for 14 days and for the three subjects studied for at least 24 days. See text for explanation. The difference in RTs was calculated as the mean RT for vibratory-cued trials subtracted from the mean RT for visually cued trials. B: The mean daily RTs for one of the monkeys during the first 24 days of training. LS= Lamp Shift (visual cue). C: The mean daily RTs during 160 days of training for one of the monkeys. Note that once the difference in RTs is established (at about 16-18 days) it is maintained throughout the remainder of the training period.

visual fixation on machinery that is of crucial importance for the task at hand. Auditory warning signals may interfere with ongoing communication. Thus, while vibratory signal have a slight disadvantage in that the information content of these signal is low compared with the spectrum of different qualities and quantities of visually and auditory information, for some applications, vibratory information processing may have the distinct advantages of being non-interfering and resulting in faster processing times. It remains to be determined what are the appropriate stimulus parameters for vibratory stimulation during complex tasks. If presented at too high an amplitude, vibratory signals may degrade motor performance by entraining the receptors which provide information about the current position of the limb and the muscle tension in that limb. If presented properly, however, vibratory information may be an important addition to the mechanisms that control complex devices and require constant vigilance on the part of the subject controlling them.

Status of Future Research:

In the continuation of this research as USAF Grant AFOSR 88-0179, we will add the remaining results of our work to the analyzed data, after having histologically confirmed the location of each cell within the somatosensory cortex. We will continue electrophysiological investigations into the nature of sensorimotor integration during active hand movement by recording from monkeys as they perform more complex tasks designed to illuminate the mechanisms involved in the changes in sensory responsiveness that occur during the initiation and execution of hand movements. We will conduct addition human psychophysical experiments designed to explore the human capacity for accurate and quick hand movements under differing stimulus-response conditions and will use the appropriate parameters determined during these experiments to guide our paradigm design for the monkey experiments. The ultimate goal is to understand the nature of the changes in neuronal sensory responsiveness that occur normally to determine how best to take advantage of the capacities of the human nervous system, while allowing for its inadequacies, as humans use their hands to control complex devices and respond to environmental cues that provide information as to the appropriate actions which the subject must take.

Listing of Written Publications:

J.T. Wall, J.H. Kaas, M. Sur, R.J. Nelson, D.J. Felleman and M.M. Merzenich. Functional reorganization in somatosensory cortical areas 3b and 1 of adult monkeys after median nerve repair: possible relationships to sensory recovery in hum[illegible]s. J. Neuroscience, 6(1):218-233, 1986.

M.M. Merzenich, R.J. Nelson, J.H. Kaas, M.P. Stryker, J.M. Zook, M.S. Cynader and A. Schoppman. Variability in hand surface representations in areas 3b and 1 in adult owl and squirrel monkeys. J. Comp. Neurol., 258:281-296, 1987.

R.J. Nelson. Activity of monkey primary somatosensory cortical neurons changes prior to active movement. Brain Res., 406:402-407, 1987.

R.J. Nelson. Set related and pre-movement related activity in primate primary somatosensory cortical neurons depends upon stimulus modality and subsequent movement. Brain Res. Bull. (In Press).

R. J. Nelson and V. D. Douglas. Premovement activity changes in primary somatosensory cortex differ when monkeys make hand movements in response to visual vs. vibratory cues. Brain Res. (submitted).

Presentations with Abstacts:

R.J. Nelson. Activity of postcentral somatosensory cortical neurons changes prior to active movement. Neuroscience Abst. 11:752, 1985.

R.J. Nelson. Sensory responses and pre-movement activity changes in primary somatosensory cortex differ when monkeys make hand movements in response to visual vs. vibratory cues. Neuroscience Abst. 13:473, 1987.

Workshop "Mechanisms of Behavior Related Sensory Gating in Neuronal Circuits" (Organizer: John K. Chapin). Winter Conference on Brain Research - January, 1987.

R.J. Nelson. The response of primary somatosensory cortical neurons changes with 'motor-set' as sensory signals are integrated with motor behavior". Review of Air Force Sponsored Basic Science Research in the Neurosciences, Brooks AFB, San Antonio, TX, November, 1987.

R.J. Nelson and V.D. Douglas. Quantitative differences in premovement activity of primary somatosensory cortical neurons during visual versus vibratory cued hand movements. Neuroscience Abst. 14: (In Press), 1988.

Neuroscience Center of Excellence Seminar, University of Tennessee, Memphis January, 1988. "Sensory Gating in the Primate Brain: Maybe Yes, Maybe No". (no abstract).

Workshop "Sensory responsiveness varies as a function of the behavioral state under which stimuli are presented" (Organizer: R.J. Nelson). Winter Conference on Brain Research - 1989.

Workshop "Serial, parallel, or massively serial" (Organizers: H. Nudelman and W.H. Calvin). Winter Conference on Brain Research - 1989. (pending approval).

Associated Personnel-

Research Assistants

Michael D. Fromke:

On 28 July 1985, Michael D. Fromke was hired as a Research Assistant with a full-time commitment to this research project. Mr. Fromke, was a recent graduate of Wheaton College and became proficient in all the technical aspects required in his position, including animal training, on- line data collection, off-line data analysis and electrode fabrication.

During Year 01 of this project, Mr. Fromke was employed as a Research Assistant, holding the position subsequently filled by Mr. Wrenn. Mr. Fromke, a rising third year medical student, worked in the laboratory during the summer of 1987. Since he previous was familiar with all aspects of the laboratory, he proved to be invaluable while searching for a replacement for Mr. Wrenn.

Edward M. Wrenn:

In August of 1986, Edward Wrenn was hired as a Research Assistant with a full-time commitment to this research project. Mr. Wrenn has been taking science courses at Memphis State University and has since become proficient in all the technical aspects required in his position, including animal training, on- line data collection, off-line data analysis and electrode fabrication. Mr. Wrenn left the laboratory in late June, 1987 to take some summer courses before beginning Medical School in the fall at the University of North Carolina at Chapel Hill. A full-time replacement was sought for his position.

John M. Byrd:

Mr. Byrd was hired as a Research Assistant with a full-time commitment to this research project, beginning in August of 1987. He was a recent graduate of Memphis State University and became proficient in all the technical aspects required in his position, including animal training, on- line data collection, off-line data analysis and electrode fabrication.

Mr. Byrd's work subsequently became unsatisfactory and he eventually took another job. He was replaced in April, 1988 by Ms. Douglas.

Vickie D. Douglas:

Ms. Douglas became the Research Assistant for this project in April of 1988. A recent graduate of Middle Tennessee State University, she began graduate work at the University of Tennessee, Memphis in the fall of 1987. She found it impossible to continue as a graduate student due to monetary concerns and was subsequently hired to fill the position vacated by Mr. Byrd. This proved to be fortuitous because she had previously been trained in this laboratory while a graduate student. She is currently responsible for all facets of the laboratory and has proved to be the most proficient Research Assistant to date.

Postdoctoral Associates

Matthew W. Wood, Jr., M.D.:

Matthew W. Wood, Jr., M.D. joined the laboratory on 2 January 1986. Dr. Wood is a neurosurgical resident who is fulfilling the laboratory experience portion of his training in this laboratory. He is sponsored by the Neuroscience Center of Excellence Grant awarded to the University of Tennessee- Memphis by the state government, and has, in the short time he was with us, become familiar with all aspects of the functionings of this laboratory. He was of great benefit in the surgical procedures and in extracellular single-unit cortical recording. Dr. Wood left the laboratory at the end of June, 1986 to become the Chief Resident in Neurosurgery at the University of Tennessee- Memphis Health Sciences Center.

Steven L. Klein, M.D.:

Steven L. Klein, M.D. joined the laboratory on 1 July 1986. Dr. Klein is also a neurosurgical resident and has been chosen to fulfill his laboratory experience in this laboratory. He is supported by the Department of Neurosurgery at U.T. Dr. Klein is somewhat unusual in that he has had previous experience recording from awake, behaving monkeys. The experience stems from a project he participated in as an undergraduate at the University of Washington- Seattle and involved recording from motor cortex in normal and epileptic monkeys. He was with us for 3-6 months.

Graduate Students on Neuroscience Rotations

Three graduate students from the Department of Anatomy and Neurobiology at the University of Tennessee, Memphis have served 3 month internships in this laboratory. They were Carl M. McCandlish (fall- 1987), Vickie D. Douglas (winter- 1988) and Bret N. Smith (spring- 1988). Each was responsible for portions of the work presented in this report. Mr. McCandlish was responsible for the human and primate reaction time study, Ms. Douglas for the comparison of vibratory and visually-cued activity and Mr. Smith for the elucidation of the relationship between vibratory responsiveness and premovement activity in vibratory responsive SI neurons.

Interactions:

Meetings attended:

1985 Meeting of the Society for Neuroscience, Dallas TX. - October 1985.
1986 Meeting of the Society for Neuroscience, Washington, D.C. - November 1986.
1987 Meeting of the Society for Neuroscience, New Orleans, LA. - November 1987.
1987 Review of Air Force Sponsored Basic Science: Research in the Neurosciences, Brooks AFB, San Antonio, TX, November, 1987.
1987 Winter Conference on Brain Research, Vail, CO. - January 1987.
1988 Winter Conference on Brain Research, Steamboat Springs, CO. - January 1987.

Ad Hoc Reviewer:

Journal of Neurophysiology - reviewed two manuscripts for publication.
Veteran's Administration- reviewed three scientific proposals.
Brain Research Bulletin- reviewed two manuscripts for publication.
National Science Foundation- reviewed two scientific proposals.

Adviser:

University of Texas at Dallas, Health Sciences Center- External Expert Scientific Reviewer for doctoral dissertation defense of Jacquiline Guise, Dept. of Cell Biology.

New Discoveries:

None.

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